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FRAMEWORK FOR STRUCTURAL ONLINE HEALTH MONITORING OF AGING AND DEGRADATION OF SECONDARY PIPING SYSTEMS DUE TO SOME ASPECTS OF EROSION

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FRAMEWORK FOR STRUCTURAL ONLINE HEALTH MONITORING OF AGING AND DEGRADATION OF SECONDARY PIPING SYSTEMS DUE TO SOME ASPECTS OF EROSION

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ABSTRACT

This paper describes the current state of research related to critical aspects of erosion and selected aspects of degradation of secondary piping systems in nuclear power plants (NPPs). The paper also proposes a framework for online health monitoring of aging and degradation of secondary piping. The framework consists of an integrated multi-sensor modality system, which can be used to monitor different piping configurations under different degradation conditions. The paper analyses the currently known degradation mechanisms and available monitoring techniques and practices. Based on this analysis, the structural health monitoring framework is proposed.

There is unanimous agreement between industry experts and academic researchers that identifying and prioritizing inspection locations in secondary piping systems would eliminate many excessive in-service inspections. The proposed structural health monitoring framework takes aim at answering this challenge by combining long range guided wave technologies with other monitoring techniques, which can significantly increase the inspection length and pinpoint the locations that degraded the most. More widely, the paper suggests research efforts aimed at developing, validating, and deploying online corrosion monitoring techniques for complex geometries, which are pervasive in NPPs

This transition to condition-based, risk-informed automated maintenance will contribute to a significant reduction of operations and maintenance costs that account for 80% of nuclear power generation costs. To address the issue of rising operating costs and economic viability, in 2017, companies that operate the national nuclear energy fleet started the Delivering the Nuclear Promise Initiative, which is a 3-year program aimed at maintaining operational focus and safety, increasing value, and improving efficiency.

Key Words: structural health monitoring, secondary systems, erosion and corrosion

1 INTRODUCTION

The LWRS Program, funded by the U.S. Department of Energy's Office of Nuclear Energy, aims to provide scientific, engineering, and technological foundations for extending the life of operating light water reactors (LWRs). This program involves several goals, one of which is ensuring safe operation of NPPs' passive components, such as concrete, piping, steam generators, heat exchangers, and cabling [1].

Within the LWRS Program, the Advanced Instrumentation, Information, and Control (II&C) Systems Technologies Pathway conducts targeted research and development to address aging and reliability concerns with the legacy analog instrumentation systems, structures, and components (SSC) and related information systems of the U.S. operating LWR fleet. This work involves two major goals: (1) ensuring legacy analog II&C systems are not life-limiting issues for the LWR fleet, and (2) to implementing digital II&C technology in a manner that enables broad innovation and business improvement in the NPP operating model. Resolving long-term operational concerns with II&C systems contributes to long-term sustainability of the LWR fleet, which is vital to the nation's energy and environmental security [2].

Reducing operations and management cost is one of the most pressing problems facing the nuclear power generation industry. Operations and maintenance costs comprise approximately 60 to 70% of the overall generating cost in legacy NPPs. Only 15 to 30% of costs are attributed to fuel. Furthermore, of the operations and maintenance costs in U.S. plants, approximately 80% are labor costs.

Falling fossil fuel prices leads to companies operating nuclear power stations to rethink their operating practices, identify opportunities, and reduce operating cost to stay competitive and avoid decommissioning. To increase economic competitiveness, the nuclear industry is targeting a 30% reduction in operating costs over the next few years. However, the target areas and mechanisms of this reduction remain unclear and represent a challenge for both utilities and research organizations.

Acknowledging that the current situation in market regime is unsustainable [3], the Delivering the Nuclear Promise initiative aims to achieve 30% reduction in nuclear power plants operating cost while maintaining the highest standards of safety. It is also acknowledged [165] that the industry needs to rethink operating practices, make bold efficiency improvements and innovation, and redesign their maintenance practices to improve efficiency and effectiveness while continuing to advance safety and reliability. Solving these problems will require paradigm shift from periodic inspections of sample locations to continuous online monitoring of some components and need-based inspections. Piping degradation due to corrosion is one of the major concerns for the U.S. Nuclear Regulatory Commission (NRC), as well as for utilities.

2 PRIMARY PIPING DEGRADATION MECHNISMS IN NPPS

2.1 Flow-assisted corrosion (FAC)

FAC is one of many corrosion mechanisms affecting piping in aging NPPs. FAC is a dissolution dominated phenomenon with moderate flow rate contribution. It should be noted that all corrosion mechanisms in NPPs' piping are "flow-assisted", however the flow contribution to the corrosion differs. FAC is primarily a corrosion process aided by chemical dissolution and mass transfer. FAC is overtaken by erosion processes at higher flow rates. FAC normally starts at flow rates of 3 meters per second (m/s), although lower flow rates are reported in the literature, and is replaced by shear stress corrosion processes at around 10 m/s in single phase flows.

In general, the FAC process consists of two steps: (1) production of soluble iron species at the oxide/water interface by anaerobic iron oxidation and (2) mass transfer of the soluble and particulate iron species to the bulk flow across the porous diffusion boundary layer. Though FAC is characterized by a general reduction in pipe wall thickness for a given plant component, FAC frequently occurs over a limited area, such as a pipe elbow, due to a local, high area of turbulence. The rate of the wall metal thinning due to FAC depends on a complex interaction of a number of parameters, such as material composition, feedwater chemistry, geometry, and hydrodynamics. Rates up to 3 millimeters per year (mm/year) have been reported [4].

2.2 Cavitation erosion

Cavitation erosion can be defined as the process of surface degradation and loss of material from the surface due to the generation of vapor or gas pockets within the flow of liquid. These pockets are formed when the pressure is low and much less than the saturation vapor pressure of the liquid. Thus, erosion is caused when vapor bubbles are lashed against the surface.

Generally, cavitation erosion is a form of an attack on the surface by vapor or gas bubbles generating a rapid collapse due to a pressure difference close to the surface. A significant low pressure below the saturated vapor pressure is created hydro-dynamically due to different factors that affect the flow. Such factors consist of liquid viscosity, temperature, pressure, and type of flow. The main reason for the deterioration of the surface is the sudden, powerful upward or forward movement of the bubbles that bombard the surface, thus causing surface deformation eventually leading to pitting.

Cavitation affects the surfaces of both metals as well as non-metals. It gives rise to unnecessary noise levels and significantly declines the useful life of materials. Certain important parts like pump impellers, propellers, and turbines can all be affected by cavitation. Not only can this damage lead to potential harm of workers and people associated with it, but also a loss of revenue, time, and energy. Hence, it incurs extra overhead costs on failure detection and analysis, repairs, and replacement work [5].

Cavitation causes a variety of defects such as leakage, wall thinning in power plant piping, and severe damage to valve internals. It also damages hydroelectric turbine blades, shop propellers, and pump internals. In the case of power plants, cavitation mostly affects control valves and downstream of orifices in liquid filled systems. Generally, cavitation damages are sudden and localized. The damaged surface is usually very rough and irregular.

2.3 Liquid Impingement Erosion

Liquid impingement erosion (LIE), often termed as liquid droplet impingement (LDI), can be defined as a gradual or progressive degradation of the parent material from a solid surface as it is continuously exposed to impacts of liquid droplets or micro jets. Impingement by liquid droplets or jets causing repetitive collisions between the discrete liquid drops and the surface that degrades due to the impact.

Impulsive contact pressures are created on the target solid surface by the discrete liquid droplets from the micro jets, the impacts of which are more extensive than those generated by steady flows. Hence, the yield strength and the limit of endurance can be exceeded, resulting in damage because of mechanical interactions. Conjoint chemical interactions also cause material loss and degradation in under certain circumstances. At very high velocities, a single liquid droplet can induce material loss from the surface. In advanced stages, erosion due to liquid impingement shows surface features which appear jagged, and are composed of sharp peaks and pits [6].

The major source of most erosion is the water entrapped in the flow of steam and the non-discharged condensate moving at very high speeds. The recurring impacts of impinged flowing water jets induce progressive wall-thinning at the bends and fittings of pipes. These water jets, due to their mass and higher impact velocity, create the damage which is analogous to that of water jet cutting [7].

2.4 Solid Particle Erosion

Similar to cavitation and liquid droplet impingement, there is another erosion phenomenon that consists of a very typical process of wear caused by virtue of material loss resulting out of repetitive impingement or impact of small solid particles which is known as Solid Particle Erosion (SPE). When a liquid or gas medium entraps hard particles which then get impacted onto a solid surface at a high velocity, this causes solid particle erosion. When SPE occurs, the solid particles undergo acceleration or deceleration, and the fluid impacting has the plausibility of changing their directions of motion. SPE can cause serious problems in several process applications in industries like: steam and jet turbines; piping systems; valves carrying particles; and fluidized bed combustion systems. SPE involves various processes. Mechanical impact, being the primary process, is caused by the impact of solid particles on the target material. There are also certain secondary processes such as thermal, chemical, and physical interactions within the counterparts during the wear mechanism. The failures of mechanical components undergoing erosion and the decreased life span have led to research and studies for a better understanding of the SPE wear phenomenon [8].

2.5 Flashing Erosion

Flashing erosion originates when the pressure of a fluid decrease below its vapor pressure, while changing from a liquid to a vapor. This process involves small vapor cavities or bubbles which are created that eat away or degrade away at the outlet of the control valve and its trimmed components. This sort of damage is earmarked by shiny, smooth gouges in material surface body. This is the stage when the fluid gets converted from a liquid to a vapor, both of which have similar chemical composition and characteristics.

The vapor pressure depends on the fluid temperature and, therefore, flashing erosion is characterized by both the pressure and temperature of the flowing fluid. For the fluid to undergo flashing, heat transfer has to occur from the liquid while vaporizing and this phenomenon needs time.

2.6 Pitting Corrosion

Pitting corrosion can be defined as the phenomena of localized areas of corrosion characterized by the formation of holes, or pits, on the material surface. The formation of these pits can either be uncovered or covered by a semi-permeable membrane of products due to corrosion. Due to the formation of these covered pits makes pitting corrosion difficult to detect and mitigate the effects thereof compared to that of uniform corrosion. Other than the localized reduction in material thickness, the pits also serve as stress points which increase the probability of fatigue and stress corrosion cracking (SCC).

3 HEALTH MONITORING OF SECONDARY PIPING COMPONENTS

Operations and maintenance costs comprise approximately 60 to 70% of the overall generating cost in legacy NPPs [163]. Replacing inspection-based maintenance with condition-based maintenance has the potential to reduce operating cost and advance safety. The current practice involves performing maintenance of active components through maintenance rules and passive components through aging management programs (AMP) [9].

The GALL report [10] (i.e., Generic Aging Lessons Learned) lists around 50 AMPs, with the overwhelming majority relying on periodic inspections during planned downtime. The periodic inspections are usually performed using NDE techniques which require extensive logistic.

Currently, all utilities implement a rigorous FAC management program that is based on a periodic maintenance strategy. Under the FAC management program, plant maintenance personnel inspect the piping during every outage using a localized technique (ultrasound, for example) to study corrosion and thinning of pipe walls. This approach is labor intensive, time consuming, and puts utilities at an economic disadvantage in comparison to other energy producing technologies, such as gas, for example. In high radiation exposure areas, it puts personnel at greater risk for radiological dosage. In addition, plant maintenance staff members have no means to monitor or estimate the increase in the rate of change in pipe corrosion on an online basis while plant is operational. Between two consecutive outages, the internal pipe wall thickness might degrade below the acceptable threshold limit and might result in pipe failure that forces an outage.

FAC management programs rely on the results of plant specific inspection data to develop plant specific correction factors, that are used to forecast degradation. This correction accounts for random uncertainties in plant data, systematic discrepancies caused by plant operation, and also for specific design features of a plant, as well as the piping replacement history. The median numbers of inspections for utilities that have relied on ultrasonic and radiography inspection data to refine wear rate predictions and have reduced susceptibility are approximately 70 large bore and 18 additional small bore locations per refueling cycle. While the number of inspection locations examined per refueling cycle is very plant-specific—depending on plant age, history, initial wall thickness, wall thickness thresholds, piping materials, length of refueling cycle, and susceptibility—the above figures reflect a sample of industry experience as of 2012 [11]. Operating experience has demonstrated that until a comprehensive analysis of all susceptible piping systems has been performed, plant personnel cannot be confident that all FAC-susceptible components have been identified and are under surveillance to prevent leakage or rupture [12].

4 CONDITION-BASED INSPECTIONS OF SECONDARY PIPING ENABLED THROUGH ONLINE STRUCTURAL HEALTH MONITORING

It is widely recognized in nuclear industry that the cost of NDE logistic is higher than the cost of NDE. For example, to perform NDE on piping systems, insulation removal and scaffolding often required to get access to bare piping. For buried piping, pipe's excavation is often the only option to get access. After all these efforts, very small number of inspections produce something that requires action. As shown in Figure 1, in the order of increased cost and lost revenue, the following four events are most damaging to an NPP's economic performance: (1) unscheduled downtime, (2) scheduled downtime, (3) anything unscheduled, and (4) cables. The two costliest events of unplanned downtime and planned downtime are directly related to the plant's maintenance. Unplanned downtime is normally caused by some equipment malfunction that has not been previously detected during in-service inspections, while planned downtime is mostly spent on performing numerous aging management programs.

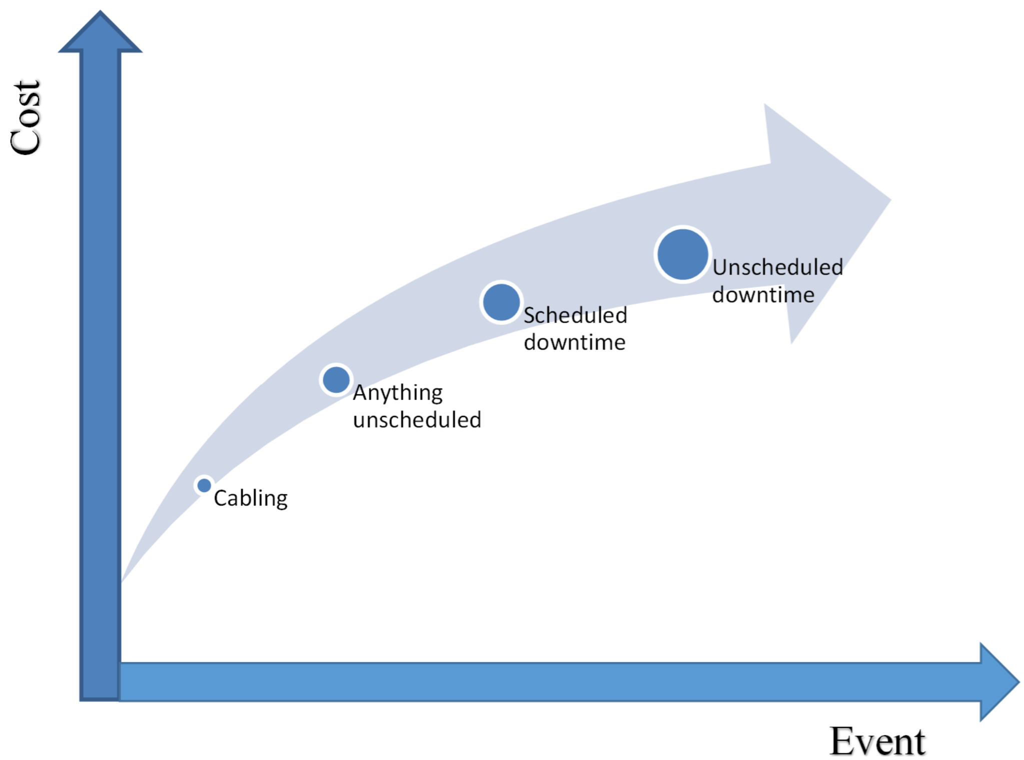

Figure 1. The costliest events that affect a plant's economic performance

To address the issue of costly downtime, the concept of online structural health monitoring (SHM) for secondary components has been introduced to nuclear industry. In contrast to the current practice of periodic inspections, online SHM offers a number of economic and technical benefits, including the following:

- Improved capacity factor by reducing unplanned and planned outages
- Improved safety through fewer unexpected failures and less repairs
- Optimized equipment operation and maintenance through early identification of faults

- Improved fault diagnostics through increased availability of data relating to faults and shared knowledge of fault behavior based on case studies and expertise
- Lifetime extension of existing NPPs by having an increased understanding of the current health of the plant components and remaining useful life estimation
- Minimizing human factors effects on non-destructive testing.

It has emerged during the discussions with utilities that monitoring mechanical integrity through inspections (online or offline) revolves around six questions that need to be answered before the inspection strategies are put in place [13]. These six questions are depicted in Figure 2.

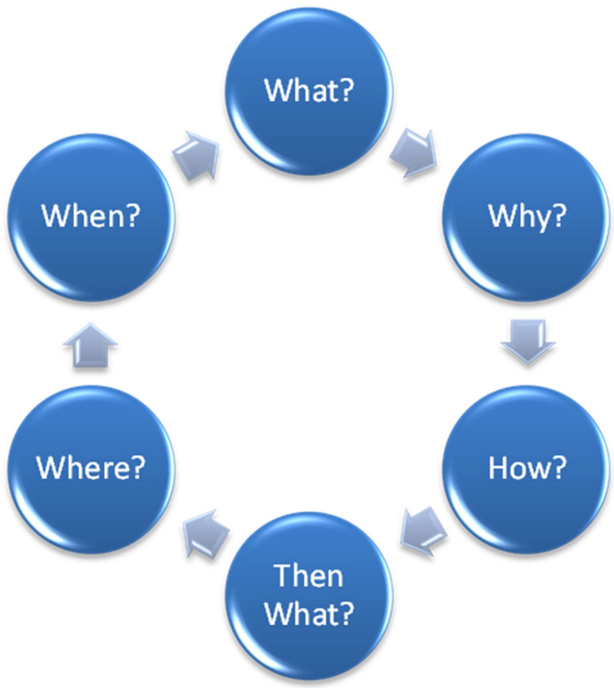

Figure 2. The six key questions that need to be answered before deploying a monitoring system.

The "What to inspect?" question was historically addressed through the Probabilistic Risk Analysis Implementation Plan and Risk-Informed Regulation Implementation Plan. It currently is addressed through the Risk-Informed and Performance-Based Plan. The "Why to inspect?" is answered by the existence of four major degradation mechanisms affecting SSCs in NPPs. The four degradation mechanisms include (1) wall thinning due to numerous corrosion and erosion processes, (2) cracking due to stress and fatigue, (3) embrittlement, and (4) structural damage such as alkali-silica reaction in concrete. The "How to inspect?" question is addressed by existing nondestructive evaluation (NDE) technologies such as surface examination technologies (e.g., magnetic particles, liquid penetrant, eddy currents, and visual inspection), volumetric examination technologies (ultrasonic and radiographic), and a recently arrived acoustical emission testing. The "Then what?" question was discussed at length at the workshop and general agreement was that raw data collected by online SHM are not actionable and algorithms are needed to convert collected online data into the NPP's decisions. The "When to inspect" question is answered by knowing the rate of damage for major degradation mechanisms listed in the "Why" question. Those rates are generally known through utilization of corrosion coupons, for example. During workshop discussions, the consensus opinion was that out of the six questions, the question of “Where to inspect” had no satisfactory answer. For example, for an NPP’s piping systems all other five questions can be readily answered. The probabilistic risk analysis will indicate piping as one of the most important safety systems, answering the “What” question. The “Why” question is addressed by known piping degradation mechanisms, while the “How” is taken care of by in-service NDE inspections. The “Then what?” and “When?” questions are also comfortably handled by existing rules and regulations. However, the “Where?” question still remains. Even for such established programs as FAC management, identification of inspection locations is complicated by several factors, including the following [13]:

The online monitoring system will have a larger area of coverage than the current NDE techniques and will aim to answer the question which current AMP programs are facing – where to inspect or identification of inspection locations. There is no currently available technology that would pinpoint which piping component need to be inspected. This is the major reason for redundant inspections.

The idea of condition-based maintenance has been embraced by many industries since 1980’s. A classic example is an introduction of tire-pressure monitoring system in automotive industry in mid-1980’s which is mandated now in U.S. since 2007. The old practice of regularly checking the tire pressure once a month is currently replaced with tire-pressure sensors which alert the driver when the tire in under or over inflated thus replacing periodic checks and adding to safety and time savings.

5 INTEGRATION OF GUIDED WAVES AND OTHER TECHNOLOGIES FOR INSPECTION OF PIPING SYSTEMS IN SECONDARY CIRCUITS OF NUCLEAR POWER PLANTS

The piping system is one of the most valuable assets in legacy NPPs, with inspections performed on a regular basis. The technical basis for the inspection period could be based on, for example, a predictive analysis or operating experience. However, because of the significant length of the piping systems, the problem of identifying specific piping components that need to be inspected during an outage remains a challenge. As a result, many unnecessary inspections are performed, which adds to planned downtime and lost revenue. The relatively recent technology of ultrasonic guided waves (GWs) offers new possibilities in the inspection of large portions of piping systems with few sensors. GWs are mechanical or elastic waves that propagate at low frequencies, sonic or ultrasonic through pipe’s walls, and bounded and guided by those walls. The velocity and wave modes of GWs are strongly influenced by the geometry of the guiding boundaries. In the pipe, the GWs exist in three different wave modes—longitudinal, torsional, and flexural. Because the GWs are mechanical waves, they are generated either through piezoelectric or magnetostrictive transducers that convert electrical of magnetic fields into mechanical energy. Once the mechanical wave is generated with a set of piezoelectric or magnetostrictive sensors arranged in a collar around the pipe, it is transmitted through the pipe’s walls and reflects back from any wall’s discontinuities.

The GWs inspection has numerous advantages over other NDE techniques, including the following:

- It can inspect large sections of piping with a single sweep
- It can inspect inaccessible locations
- Its sensors can be mounted permanently
- It may be used for inspection while the system is operating
- It can inspect pipes from 2 to 96-in. diameter.

In contrast to conventional UT inspections, the GW technology can cover tens of meters in one inspection session. The traditional UT inspections are highly localized and can only detect flaws within proximity of the sensor location.

Despite all of these benefits, the GW technology is challenged when applied to power plants in general and to NPPs in particular. Piping systems in electric power plants come in various configurations and geometries; for example, they have thousands of elbows, bends, tees, valves, and flanges. These geometries are not a friendly media for GWs. The geometries other than strait pipe attenuate and distort the GWs, making inspections beyond them difficult. Also, while being a perfect tool for locating the damage in pipes, GWs cannot determine the size of the flaw with acceptable accuracy. In summary, provided the GW technology can overcome the limitations of complex geometries, it is a perfect tool for answering the "Where to inspect?" question. However, to fully cover all types of piping geometries uncounted in NPPs, the GWs technology needs to be augmented with other sensors modalities capable to monitor complex geometries.

5.1 Piezoelectric Paint Technology

Piezoelectricity is the ability of certain materials to generate an electrical field when subjected to mechanical stress or, alternatively, to generate mechanical strain in response to applied electrical charge. The former property is called direct piezoelectric effect, while the latter is called inverse piezoelectric effect. Piezoelectric sensors are one of the most widely used sensors in NDE due to their ability to generate electrical charge in response to mechanical load without an external power source. Traditionally, piezoelectric sensors are made of ferroelectric ceramics, are brittle, and cannot be applied to curvatures or complex geometries. To overcome this limitation, ferroelectric composite can be formed as a combination of piezoelectric ceramics and piezoelectric polymers. The ferroelectric composite combines the excellent piezoelectric response of ceramics with the flexibility of polymers, creating a piezoelectric paint sensor. The piezoelectric paint has been known since the 1980s [14]; however, recent technological advances in its manufacturing made this technology a frontrunner for many applications that require the sensor to conform to complex geometries.

5.2 Impedance Monitoring Approach

Dynamic electrochemical impedance spectroscopy (DEIS) technique gives a scope for a creative approach towards the evaluation and monitoring of cavitation erosion-corrosion degradation. Along those lines, there is evidence of the impact due to cavitation exposure on the factors responsible for impedance and also the rate of failure of the surface of the sample. Reversible outcomes due to the degradation of the corrosion product layer and an increased mass flow rate have been observed due to impedance.

5.3 Equipotential Switching Direct Current Potential Drop Approach

K. H. Ryu et al. [15] suggested the implementation of an Equipotential Switching Direct Current Potential Drop (ES-DCPD) system which could be used effectively for predicting the rate of loss of thickness of the walls in the piping systems. The inspection from Ultrasonic Testing appeared to be in good agreement with the ES-DCPD. It has been observed that the ES-DCPD technique can be applied to a wide range of area for identifying the thinned location. The Narrow Range Monitoring (NaRM) can be utilized for a localized area. When it comes to precise prediction of the location of maximum wall thinning, NaRM is a better and more advisable method than online UT method. The ES-DCPD NaRM has a better resolution and sensitivity. Its performance is quite stable and reliable under different temperature and radiation environments.

6 MULTI-SENSOR FRAMEWORK FOR MONITORING SECONDARY PIPIING COMPONENTS IN NPPS

Since the nuclear power plants piping has complex geometries, it is impossible to offer a single sensor modality that would be able to collect data from the whole piping component. Taking this into account, the complete coverage of the piping system with online monitoring sensing will require several sensor modalities applied to different geometries, such as elbows, flanges, valves, and tees. This justifies the need for multiple monitoring development projects which will draw ideas from sensors modalities reviewed in the previous section. The exact number of these sensor modalities will be defined after the development phase is complete, however the current thinking is that four new monitoring technologies, combined with already existing, such as GW will be sufficient to monitor the entire piping system.

During the development phase a data acquisition structure will be established which would be able to collect data from different sensor modalities. Currently, different online monitoring technologies collect data in different formats, with different sampling rates, and with different accuracy. A common data acquisition structure will be needed to reconcile these data streams and make them usable in online monitoring system.

It is envisioned that online integrated monitoring system, will perform data processing, data fusion, and decision making to provide end users the status of the piping system, specifically evaluation of wall thickness and the remaining useful life of pipes. The integrated online monitoring system will interface with the data acquisition structure by accessing reconciled data files created by the latter. The conceptual representation of the system's output is shown in Figure 3.

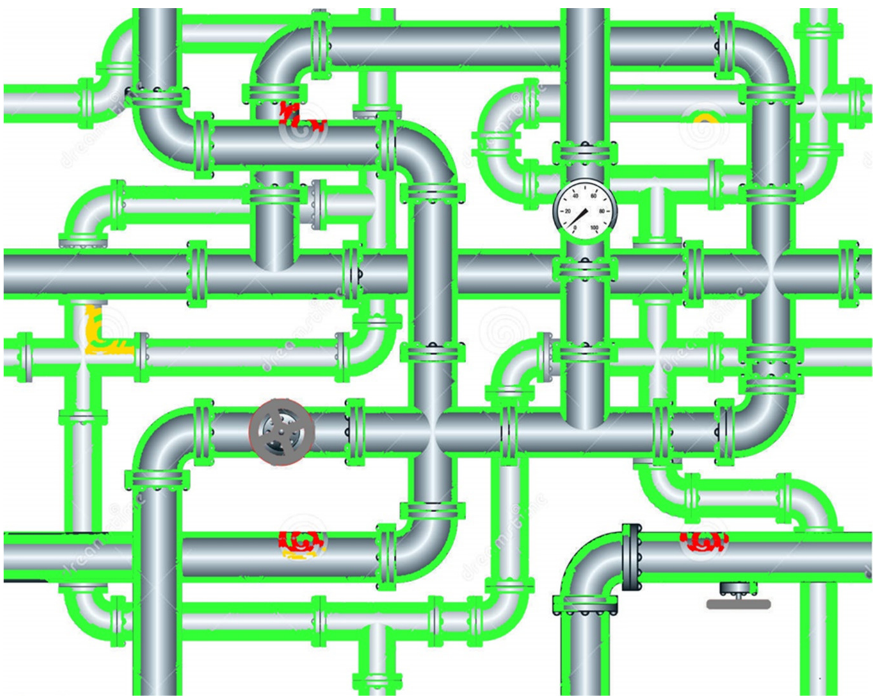

Figure 3. Conceptual representation of the online monitoring system's output. The wall thickness is color coded with green representing the safe thickness, yellow-borderline thickness, and red representing the wall thickness close to safety threshold, which requires immediate attention.

7 CONCLUSIONS

This paper describes the comprehensive approach for tackling the problem of identifying and prioritizing inspection locations in NPP piping systems. Based on utilities feedback, it is obvious that one of the most pressing problems is reduction of planned piping inspections in nuclear SSCs, which would reduce the operating and maintenance cost and increase the economic viability of legacy NPPs. This approach combines several state-of-the-art technologies used in nondestructive examination. The proposed techniques are complimentary because GWs use the properties of other sensor modalities to increase their propagation range in complex geometries. The piezoelectric paint and other sensor modalities acts as a waveguide for the GWs, thus allowing them to deal with complex geometries that are often present in NPPs' piping systems.

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